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The MOJAVE Program: Studying the Relativistic Kinematics of AGN Jets

Matthew L. Lister

Department of Physics, Purdue University, West Lafayette, IN 47907

Abstract. We discuss a new VLBA program to investigate structural and polarization changes in the brightest AGN jets in the northern sky. Our study represents a significant improvement over previous surveys in terms of image fidelity, size, and completeness, and will serve to characterize the kinematics of AGN jets and determine how these are related to other source properties. We discuss several preliminary results from our program, including the detection of parsec-scale circularly polarized jet emission, enhanced magnetic field ordering at the sites of apparent bends, and intrinsic differences in the jets of strong- and weak-lined AGN.

1. Introduction

Kinematic studies using very-long-baseline interferometry have greatly increased our understanding of extragalactic jets on parsec-scales, but there are still many questions regarding their dynamics and evolution that remain unanswered. This is partially due to the lack of a long-term, systematic, full-Stokes imaging survey of a large complete sample in which the selection effects are well-understood. MOJAVE (**M**onitoring **O**f **J**ets in **A**GN with **V**LBA **E**xperiments) is a new VLBA program that is designed as a follow-up to the VLBA 2 cm survey (Kellermann et al. 1998). It is currently investigating structural and polarization changes in the 134 brightest AGN jets in the northern sky, of which 98 were part of the original VLBA 2 cm Survey. The main goals of MOJAVE are to:

- Measure the distribution of apparent jet speeds, both within individual sources and for the entire population.
- Determine whether jet speed is related to other intrinsic quantities, such as luminosity, black hole mass, and emission line strength.
- Characterize the kinematics of moving jet features, and determine whether they are consistent with streaming paths along bent trajectories.
- Investigate how magnetic fields evolve within the jets, and how they track the moving features.
- Search for parsec-scale circularly polarized jet emission, and examine how it evolves with time.

2. Sample Selection and Observational Status

The goals of our program require a complete sample of extragalactic jets that is large enough to investigate statistical aspects of the parent population, and to perform inter-comparisons between various sub-classes, such as quasars, BL Lacertae objects, gamma-ray loud sources, and intra-day variables. Whereas the selection criteria of the 2 cm VLBA survey were loosely defined in order to include a wide range of sources such as gigahertz-peaked spectrum objects and radio galaxies, the MOJAVE sample is selected purely on the basis of compact radio flux density. The latter choice ensures a high degree of completeness since a) all known AGN jets are radio-loud, b) all-sky radio surveys are available at several frequencies, c) all our sources are detectable by the VLBA. Another benefit is that we are able to directly compare our data to Monte Carlo simulations of relativistic beaming, without worrying about contamination from extended, steep-spectrum emission. Also, the radio emission comes from the same region as where we are measuring the apparent jet speeds, which is important when estimating Doppler beaming factors from the kinematic data. Our specific selection criteria are: a) declination $> -20°$, b) galactic latitude $|b| > 2.5°$, and c) total 2 cm VLBA flux density ≥ 1.5 Jy at any epoch since 1994 (≥ 2 Jy for sources with $\delta < 0°$).

By not restricting our flux density criterion to a single epoch, we have included many interesting variable sources that might have otherwise been omitted. Our final sample consists of 129 confirmed and 5 candidate objects. We are currently gathering single-dish and VLBA data on the latter to determine whether they meet our selection criteria. Thirty-four of our sources are members of the third EGRET gamma-ray catalog, and broken down by optical classification there are 95 quasars, 21 BL Lacs, 10 radio galaxies, and 8 unidentified objects. Redshift information is currently available for 90% of the sample.

Since the start of our observations in May 2002, we have obtained single-epoch polarization images for 95% of the sample, and 13 sources have been imaged at more than one epoch. As of Sept. 2003, we have had ten successful observing sessions, of which nine have been fully reduced. Our observations are currently planned to continue into 2004, and we have been allotted one new 24-hour long session every six to eight weeks. We are able to observe eighteen sources each session, which implies that each source is observed roughly once per year. There are many highly variable sources that need more frequent sampling, however, so we try to observe these more often at the expense of longer monitoring intervals for the other sources. We are also monitoring our sample at cm-wavelengths with the UMRAO and RATAN telescopes to monitor overall spectral changes and to calibrate our polarization vectors.

3. Preliminary Results

3.1. Linear Polarization

We have detected linearly polarized emission in all 123 jets we have imaged thus far, with the exception of NGC 1052 and 2021+614. The latter are likely heavily depolarized by intervening gas in the host galaxy (see, e.g., Vermeulen et al. 2002). The unresolved cores (located close to the base of the jet) are

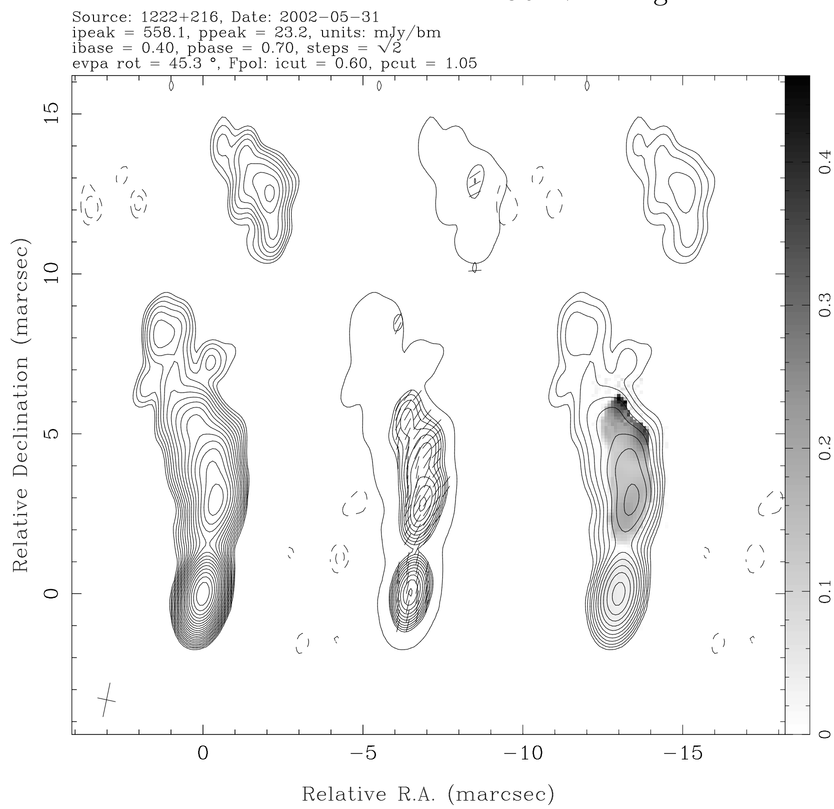

Figure 1. VLBA 2 cm images of the quasar 1222+216. Left image: total intensity contours. Middle image: linear polarization contours with electric vectors superimposed. Right image: total intensity contours with fractional polarization greyscale ranging from 0 to 40%. The restoring beam has dimensions 1.08 × 0.57 mas, and the rms noise in the I image is 0.2 mJy/beam.

weakly polarized, with the majority having fractional polarizations under 4%. Six cores (3C 111, 4C 39.25, M87, 1413+135, 2008−159, and 2128−123) have no detectable polarization. In most cases the magnetic field order increases with distance down the jet, with features in the jets being appreciably more polarized than the cores. In many sources (e.g., 1222+216; Fig. 1), the field appears highly ordered on the outside edge where the jet bends, suggesting a compression of the field from interaction with the external medium.

3.2. Jet polarization versus optical line strength

The question of whether the jets of weak-lined blazars (BL Lacertae objects) are intrinsically different than those of broad-lined blazars (radio-loud quasars) is still not fully resolved, in large part due to uncertainties associated with projection and relativistic beaming effects. One basic test involves looking for differences in the jet polarization properties of these two classes. In Figure 2 we plot the distribution of fractional polarization for polarized features in the jets of BL Lacs and quasars in our sample. A Kolmogorov-Smirnov test on the two distributions indicates only a 0.1% probability that they are from the same parent distribution.

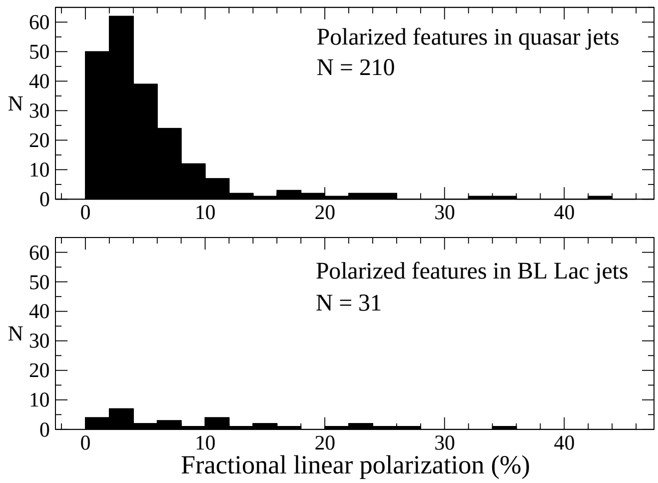

Figure 2. Top panel: distribution of fractional linear polarization for polarized features in quasar jets. Lower panel: distribution for features in BL Lacertae jets.

Further evidence for intrinsic differences can be found in a plot of fractional polarization versus distance from the core (Fig. 3). The majority of the BL Lac jet components are more highly polarized *at a given projected distance down the jet* than those of the quasars. This confirms an earlier result obtained at 7 mm by Lister (2001) for the smaller Pearson-Readhead AGN sample. Fig. 3 also shows a weak trend of increasing fractional polarization down the jet, which suggests that the magnetic fields of quasar jets take longer than the BL Lac jets to become organized. It is noteworthy that these polarization differences are located well outside the broad-line region where the optical emission lines are produced. Further investigation is required to determine whether these reflect intrinsic differences in the interstellar medium of the host galaxy, or in the jet itself.

3.3. Circular Polarization

The large number of sources that we observe at each epoch makes our survey ideal for calibration of both linear and circular polarization (CP). Using the techniques of Homan et al. (2001), we have detected weak parsec-scale circularly polarized jet emission in 8 of 68 sources analyzed thus far. Since the CP level is variable in many sources, we anticipate on having a sufficient number of detections to look for correlations between linear and circular polarization levels, and monitor the CP sign consistency over time. We also intend to examine whether circularly polarized jets possess any peculiar characteristics that distinguish them from other sources.

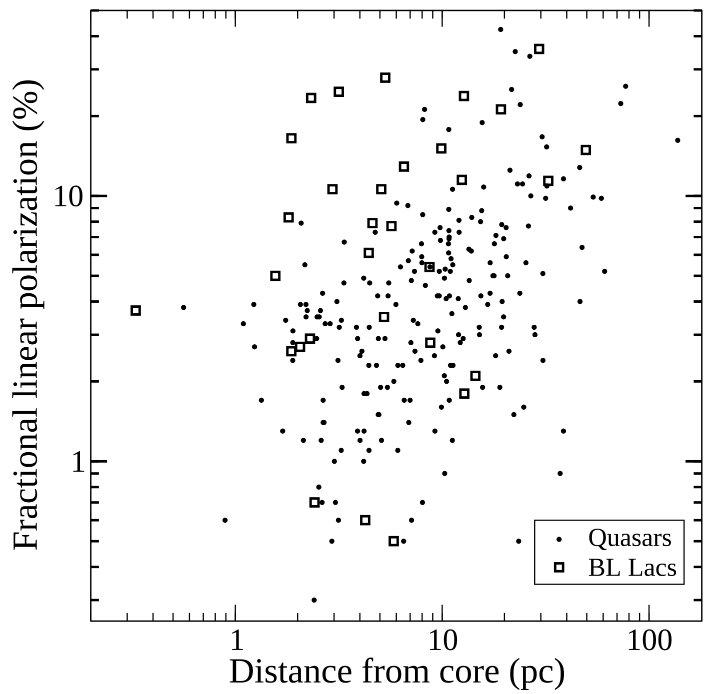

Figure 3. Plot of fractional linear polarization versus projected distance from the core for polarized features in the jets of quasars (circles) and BL Lacertae objects (open squares) .

4. Summary

The MOJAVE program represents the first large-scale, systematic survey of a complete sample of AGN jets in all four Stokes parameters. Its main goals are to obtain a better understanding of the kinematics and magnetic field structures of relativistic jets, and determine how these are related to other host galaxy properties such as the emission line strength and black hole mass. A more thorough description of our program and access to our on-line database can be found at http://www.physics.purdue.edu/∼mlister/MOJAVE.

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References

Homan, D. C., Attridge, J. M., & Wardle, J. F. C. 2001, ApJ, 556, 113

Kellermann, K. I., et al. 1998, AJ, 115, 1295

Lister, M. L. 2001, ApJ, 562, 208

Vermeulen, R. C., et al. 2003, A&A, 401, 113